AN EVALUATION OF GLERL'S HYDROLOGICAL OUTLOOK PACKAGE

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ABSTRACT: The Great Lakes Environmental Research Laboratory developed a series of physically-based conceptual models for making deterministic or probabilistic outlooks of large lake hydrology, including net basin supplies and lake levels, which consider existing basin moisture and lake heat storages and National Weather Service forecast meteorology. The performance of GLERL's Hydrological Outlook Package, used in a simulated operational application, is evaluated for the period from August 1982 through December 1988. Two subperiods, which have extreme and extremely different net basin supplies, are evaluated as well. Considering all 3 evaluation periods, deterministic outlooks of net basin supplies are best on Lake Superior. Deterministic outlooks, however, have inherent limitations, since they provide only a single forecast time series. Alternatively, probabilistic outlooks explicitly communicate the uncertainty and potential diversity of future hydrometeorologic conditions. Our probabilistic net basin supply outlooks are most informative for 1-month forecasts for Lakes Michigan, Superior, and St. Clair. Improvements in forecasting depend on better National Weather Service monthly and seasonal weather outlooks, and better selection of historic meteorologic sequences to use as forecast scenarios.

Introduction

The Great Lakes Environmental Research Laboratory developed a series of physically-based conceptual models for making deterministic or probabilistic outlooks, six or more months into the future, of large lake hydrologic components, including basin moisture storage conditions, basin runoff, lake heat storage, lake evaporation, net basin supplies, and lake levels. This paper evaluates the performance of the GLERL's Hydrological Outlook Package, used in a simulated operational setting, applied to each of the upper Great Lakes for the period from August 1982 through December 1988. Package performance during two subperiods is also examined: January 1984-October 1986, and November 1986-June 1988. While not extensive, these subperiods have particular importance because they represent extreme, and extremely different, conditions. As explained in detail by Lee and Noorbakhsh (1990) and Southam and Yee (1990), the former subperiod features persistent and extreme wet conditions, while the latter is a subperiod of extended and severe drought. Further, we are most interested in forecast performance under extreme net basin supply and lake level conditions, since that is when accurate forecasts are most urgently needed.

After describing some general aspects of the forecast evaluations, we examine a deterministic application of the package, which produces a single 6-month forecast of net basin supplies each month. We also examine a probabilistic application of the package, whereby several 6-month time series of net

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basin supplies are forecast each month. This latter approach enables expressions of confidence to be assigned to operational forecasts, and makes clear the uncertainty inherent in any forecast of future hydrometeorologic conditions. For each application, sources of forecast error are examined.

General Forecast Approach

The outlook package is described in detail by Croley and Hartmann (1990). Briefly, conceptual models of basin runoff and lake evaporation are used with near real-time meteorologic data to update estimates of current basin moisture and lake heat storage conditions, respectively. Current storage condition estimates then serve as initial conditions in model applications using forecast meteorologic sequences. The selection of forecast meteorology is important, but difficult. Typically, we select one or several historic meteorologic sequences, representing anticipated meteorology, based on the National Weather Service (NWS) monthly and seasonal forecasts of precipitation and air temperature probabilities (Climate Analysis Center 1990). The resulting forecasts for basin runoff, lake evaporation, and overlake precipitation are combined to produce net basin supply outlooks for each lake. Water level outlooks can then be determined by considering initial lake levels, the regulation plans for Lakes Superior and Ontario, and hydraulic routing through the unregulated lakes (Hartmann and Croley 1987). Uncertainties in the water supply and lake level forecasts are thus reflected, in part, by the uncertainties of the meteorologic outlooks.

The forecast evaluation consists of generating 6-month forecasts for each month of the various comparison periods. There are 77 such forecasts for the August 1982-December 1988 period, each 6 months long; the sample size thus ranges from 77 for the first month to 72 for the sixth month into the forecast. NWS meteorologic probabilities are not available prior to August 1982 in their present form, and net basin supply data sufficient for meaningful comparisons were not available after December 1988. For the two subperiods, the sample size for evaluation is unchanging (34 and 20 for the January 1984-October 1986 and November 1986-June 1988 subperiods, respectively). This reflects the availability of 2nd through 6th month net supply forecasts from the five months preceding each subperiod. (This was not possible for the full evaluation period, since NWS outlooks are not available to generate forecasts for the five months preceding August 1982.)

For all evaluations, GLERL's outlook package was used in a simulated operational setting. Thus, meteorologic data sets used in estimating current basin moisture and lake heat storage conditions were updated using only those stations that presently report in near real-time. Use of historic meteorology as forecast meteorology was limited to the period from January 1948 through 24 to 35 months prior to any specific forecast (e.g., 1979 for the August 1982 forecast); this reflects the extensive operational lag in updating historic meteorologic data sets. Selection of forecast meteorology was subjective, but the forecaster used consistent criteria for selecting those historic sequences that, in some sense, matched the NWS weather outlooks; this is discussed in more detail in the following sections. Further, the forecaster was provided with the NWS precipitation and air temperature probabilities for each month without identification of its corresponding year. Thus, selection of historic meteorologic sequences to use as forecast scenarios was accomplished without bias by knowledge of actual weather conditions of specific months during the evaluation periods.

Deterministic Outlooks

Ostensibly, Great Lakes users demand a single time series of forecast net basin supplies or lake levels for their decision making. Such preferences may reflect overconfidence in existing forecast technology and lack of experience in using probabilistic concepts in decision making. Regardless, some uses, such as the regulation plans for Lakes Superior and Ontario, presently require a single forecast of net basin supplies, and U.S. monthly water level forecasts (U.S. Army Corps of Engineers 1990) are presently issued as deterministic sequences. Thus, GLERL's Hydrological Outlook Package was also used to create deterministic forecasts of net basin supplies. These forecasts can then be readily compared to net basin supply forecasts produced by other methodologies, specifically the 50% probability forecasts presented in Southam and Yee (1990) and the trend and regression forecasts of Lee and Noorbakhsh (1990).

Beyond concerns about modeling concepts and the general approach for identifying historic meteorologic sequences that match NWS probabilities, the crux of developing deterministic outlooks is deciding how to ultimately produce only a single best forecast net basin supply time series. One approach would be to use all historic meteorologic sequences, corresponding to the period of interest, as equally likely scenarios, and then to either select the resulting median cumulative net basin supply for progressively longer periods (i.e., 1-month, 2-month, . . ., 6-month), or average the results in some other way. This approach, however, ignores the limited but acknowledged skill of NWS monthly and seasonal weather outlooks. Alternatively, a biased sample of historic meteorologic sequences, all matching the NWS weather outlooks in some sense, could be used, and then the separate net basin supply forecasts could be averaged by selecting the cumulative mean or median. However, the biased sample will surely contain some historic meteorologic sequences that don't match the NWS weather outlooks as well as others, thus "corrupting" forecasts derived only from those better-matched sequences. Thus, for purposes of this evaluation, for each forecast we simply selected the single historic meteorologic sequence that best matched the NWS 1-month and 3-month weather outlook probabilities.

While many years of the historic record have probabilities that match, within 3 percentage points, the NWS probability outlooks for a single category (1-month precipitation, 1-month temperature, 3-month precipitation, 3-month temperature), few years match the NWS outlooks for all categories. Often, compromises were required (e.g., sacrificing a close match on the 3-month precipitation probability but getting matches within 3 percentage points for the remaining categories) in selecting the single year from the historic record that best reflected the NWS meteorologic outlook. Further, some NWS outlooks called for conditions so extreme that they were unprecedented in the available historic record; for those cases, the "best" match required compromise in typically several categories.

To assess the efficacy of our Hydrological Outlook Package in a deterministic application, we compare forecast and actual net basin supplies and components (basin runoff, overlake precipitation, lake evaporation) for the overall evaluation period (August 1982 - December 1988), the "wet" period (January 1984 - October 1986), and the "dry" period (November 1986 - December 1988). The evaluation approach follows that used by Croley and Hartmann (1987) in evaluating an earlier version of the outlook package applied to Lake Superior. We calculate mean monthly measures of agreement, such as root mean square error, bias, and correlation, that are valid for evaluation with relative comparisons of different forecasting approaches. Note that since the NWS weather outlooks cover only a maximum of 3 months, the water supply forecasts 4 to 6 months into the future depend on meteorologic forecasts only via the persistence of basin runoff and lake evaporation; thus, while statistics are presented for all 6 months of the forecasts, our evaluation is limited to the first 3 months.

Statistics comparing forecast net basin supplies to actual supplies are shown in Table 1 for the entire evaluation period, Table 2 for the "wet" period, and Table 3 for the "dry" period. Net basin supplies, especially for Lakes St. Clair and Erie, are highly variable, as indicated by standard deviations that are large relative to their respective means. For the overall evaluation period, the outlook package performs best on Lake Superior, followed by Lakes Erie and St. Clair. Lake Superior forecast statistics are relatively uniform throughout the 6-month forecast period, while performance drops off after the first month for Lakes St. Clair and Erie. Table 2 shows net basin supplies to be much higher during the "wet" evaluation period. Outlooks during this period likewise gave higher supplies; however, the forecast supplies were not as extreme as actually occurred, resulting in underestimates of net basin supplies for all months and all lakes. Outlook statistics during the wet period were improved for Lake Superior for all months, and for Lake Huron for the first month. Table 3 shows net basin supplies to be extremely low during the "dry" evaluation period, with reduced variability as well, indicating persistent drought conditions. Outlooks during this period gave lower supplies only for Lakes Superior and Michigan; forecast supplies for Lake Erie were as high as during the "wet" period.

Because net basin supply forecasts are the sum of forecasts for basin runoff, overlake precipitation, and lake evaporation, it is useful to examine outlook performance for each of these respective components. Tables 4, 5, and 6 compare forecast and actual conditions for each of the components and air temperatures (important for modeling of basin runoff and lake evaporation) for the entire evaluation period, the "wet" period, and the "dry" period, respectively. Statistics are presented only for the first month of the outlooks.

The relatively high correlation for air temperatures for all evaluation periods reflects the strong seasonality of air temperatures; regardless of the historic sequence selected to use as forecast meteorology, the seasonal cycle of air temperatures was generally preserved. For the entire evaluation period, the bias is relatively small for Lakes Superior and Huron. However, temperatures are significantly overestimated on Lake Michigan for all months of the forecast, which subsequently affects the forecasting of both evaporation and runoff for that basin. For Lakes Superior, Michigan, and Erie, the second month statistics are poorer than even for subsequent months, suggesting that the NWS 3-month outlooks misdirected selection of historic meteorology sequences. The "wet" period was also a warm period, particularly for Lakes Superior and Michigan. The air temperature forecasts during this period are quite good, although they drop off and are comparable to the entire evaluation period after the first month. This suggests that during the "wet" period, both the NWS 1-month forecasts and selection of historic meteorologic sequences were good. The "dry" period, by contrast, was a cool period on all lakes, with generally reduced variation as well. Except for Lake Michigan, historic sequences used as forecast meteorology reflected the reduced temperatures, although they were too extreme on Lakes Superior and Huron and too moderate on Lakes St. Clair and Erie. Statistics are much poorer after the first month, suggesting that the NWS 3-month outlooks were poor for this period, or a lack of suitable sequences in the limited historic record.

The precipitation outlooks for all evaluation periods are notably poor. There is little correlation between forecast and actual precipitation for the upper lakes and essentially no correlation on Lake Erie. The poor precipitation statistics suggest that both the 1-month and 3-month NWS precipitation outlooks are poor. Although the "dry" period was extremely dry, the precipitation forecasts didn't follow suit. The poor statistics during this period also reflect an inability to find sequences in the limited historic record (only 33-39 years were used) that matched the NWS outlooks; consideration of the 1930s (a severe drought period throughout the Great Lakes region) may have provided more appropriate forecast meteorologic sequences.

Although runoff is closely related to precipitation, forecast statistics are much better for runoff, for all evaluation periods, for all lakes. This reflects the near real-time estimation of basin moisture storage conditions for use as initial conditions in making runoff forecasts, and the intrinsic memory provided by these storages, which reduces the sensitivity of basin runoff to short-term meteorologic variations. First month statistics are much better, for all evaluation periods, than for later months, suggesting that the persistence provided by moisture storages begins to be overshadowed by meteorologic variability

Table 1. Comparison Statistics of Actual and Forecast Net Basin Supplies During August 1982 - December 1988.

Month	Mean Actual (ft)	Standard Deviation Actual (ft)	Mean Model (ft)	Root Mean Square Error (ft)	Bias (ft)	Correlation Coefficient
LAKE SUPERIOR						
1	0.24	0.20	0.23	0.15	0.02	0.78
2	0.24	0.20	0.22	0.17	0.02	0.75
3	0.24	0.20	0.18	0.19	0.06	0.72
4	0.24	0.20	0.21	0.17	0.03	0.72
5	0.24	0.21	0.22	0.15	0.02	0.80
6	0.24	0.21	0.22	0.17	0.02	0.73
LAKE MICHIGAN						
1	0.27	0.19	0.24	0.20	0.03	0.53
2	0.27	0.20	0.23	0.22	0.04	0.48
3	0.27	0.20	0.19	0.21	0.08	0.57
4	0.27	0.20	0.19	0.23	0.09	0.50
5	0.27	0.20	0.15	0.27	0.13	0.46
6	0.27	0.20	0.22	0.23	0.06	0.55
LAKE HURON						
1	0.30	0.23	0.28	0.21	0.02	0.53
2	0.30	0.23	0.27	0.24	0.03	0.49
3	0.30	0.23	0.27	0.24	0.03	0.43
4	0.30	0.23	0.27	0.24	0.03	0.47
5	0.30	0.23	0.25	0.24	0.06	0.46
6	0.30	0.23	0.26	0.25	0.04	0.44
LAKE ST. CLAIR						
1	1.15	1.27	1.26	0.92	-0.10	0.74
2	1.17	1.27	1.31	0.97	-0.14	0.67
3	1.19	1.27	1.33	1.29	-0.15	0.48
4	1.20	1.28	1.07	1.22	0.13	0.49
5	1.20	1.28	1.11	1.39	0.09	0.40
6	1.18	1.28	1.00	1.10	0.18	0.58
LAKE ERIE						
1	0.21	0.32	0.23	0.23	-0.02	0.73
2	0.22	0.32	0.26	0.30	-0.04	0.60
3	0.22	0.32	0.21	0.29	0.01	0.65
4	0.23	0.32	0.19	0.28	0.03	0.64
5	0.23	0.32	0.19	0.27	0.03	0.68
6	0.22	0.32	0.22	0.26	0.00	0.65

Table 2. Comparison Statistics of Actual and Forecast Net Basin Supplies During January 1984 - October 1986.

Month	Mean Actual (ft)	Standard Deviation Actual (ft)	Mean Model (ft)	Root Mean Square Error (ft)	Bias (ft)	Correlation Coefficient
LAKE SUPERIOR						
1	0.27	0.20	0.28	0.13	0.01	0.84
2	0.27	0.20	0.24	0.14	0.04	0.87
3	0.27	0.20	0.24	0.15	0.05	0.86
4	0.27	0.20	0.24	0.16	0.04	0.75
5	0.27	0.20	0.25	0.12	0.04	0.90
6	0.27	0.20	0.25	0.16	0.03	0.81
LAKE MICHIGAN						
1	0.34	0.20	0.30	0.20	0.04	0.58
2	0.34	0.20	0.26	0.19	0.08	0.64
3	0.34	0.20	0.24	0.20	0.10	0.67
4	0.34	0.20	0.24	0.23	0.10	0.51
5	0.34	0.20	0.19	0.27	0.15	0.50
6	0.34	0.20	0.23	0.24	0.11	0.60
LAKE HURON						
1	0.37	0.20	0.29	0.18	0.07	0.71
2	0.37	0.20	0.30	0.24	0.07	0.53
3	0.37	0.20	0.32	0.22	0.05	0.51
4	0.37	0.20	0.31	0.21	0.05	0.63
5	0.37	0.20	0.29	0.24	0.08	0.48
6	0.37	0.20	0.26	0.25	0.11	0.55
LAKE ST. CLAIR						
1	1.53	1.58	1.32	1.14	0.21	0.71
2	1.53	1.58	1.45	1.20	0.08	0.66
3	1.53	1.58	1.50	1.53	0.03	0.45
4	1.53	1.58	1.10	1.46	0.44	0.51
5	1.53	1.58	1.04	1.63	0.49	0.40
6	1.53	1.58	0.95	1.33	0.58	0.65
LAKE ERIE						
1	0.30	0.35	0.26	0.25	0.04	0.73
2	0.30	0.35	0.29	0.32	0.01	0.59
3	0.30	0.35	0.27	0.29	0.03	0.66
4	0.30	0.35	0.17	0.32	0.13	0.63
5	0.30	0.35	0.20	0.26	0.10	0.75
6	0.30	0.35	0.24	0.30	0.06	0.60

Table 3. Comparison Statistics of Actual and Forecast Net Basin Supplies during November 1986 - December 1988.

Month	Mean Actual (ft)	Standard Deviation Actual (ft)	Mean Model (ft)	Root Mean Square Error (ft)	Bias (ft)	Correlation Coefficient
LAKE SUPERIOR						
1	0.14	0.18	0.17	0.15	-0.03	0.82
2	0.14	0.18	0.18	0.18	-0.04	0.75
3	0.14	0.18	0.12	0.18	0.03	0.66
4	0.14	0.18	0.17	0.14	-0.03	0.78
5	0.14	0.18	0.19	0.14	-0.05	0.83
6	0.14	0.18	0.21	0.16	-0.06	0.81
LAKE MICHIGAN						
1	0.20	0.16	0.17	0.19	0.03	0.51
2	0.20	0.16	0.21	0.24	-0.00	0.26
3	0.20	0.16	0.20	0.20	0.01	0.36
4	0.20	0.16	0.19	0.23	0.02	0.37
5	0.20	0.16	0.15	0.21	0.05	0.38
6	0.20	0.16	0.25	0.24	-0.05	0.45
LAKE HURON						
1	0.17	0.16	0.29	0.20	-0.13	0.66
2	0.17	0.16	0.27	0.20	-0.10	0.69
3	0.17	0.16	0.28	0.19	-0.11	0.66
4	0.17	0.16	0.27	0.22	-0.11	0.46
5	0.17	0.16	0.26	0.17	-0.09	0.73
6	0.17	0.16	0.30	0.24	-0.14	0.63
LAKE ST. CLAIR						
1	0.83	0.81	1.29	0.78	-0.46	0.86
2	0.83	0.81	1.35	0.84	-0.52	0.67
3	0.83	0.81	1.28	1.16	-0.45	0.47
4	0.83	0.81	1.26	1.04	-0.43	0.58
5	0.83	0.81	1.34	1.42	-0.51	0.52
6	0.83	0.81	1.32	0.93	-0.49	0.72
LAKE ERIE						
1	0.16	0.23	0.29	0.26	-0.13	0.70
2	0.16	0.23	0.31	0.30	-0.15	0.66
3	0.16	0.23	0.29	0.29	-0.13	0.64
4	0.16	0.23	0.28	0.26	-0.12	0.74
5	0.16	0.23	0.29	0.33	-0.13	0.59
6	0.16	0.23	0.24	0.25	-0.08	0.76

Table 4. One-Month Outlook Error Statistics for August 1982 - December 1988.

	Mean Actual*	Standard Deviation Actual*	Mean Model*	Root Mean Square Error*	Bias*	Corr. Coeff.
LAKE SUPERIOR						
Air Temperature	2.90	11.50	3.06	6.76	-0.16	0.84
Precipitation	0.23	0.10	0.24	0.10	-0.01	0.45
Runoff	0.17	0.09	0.18	0.06	-0.01	0.73
Evaporation	0.16	0.14	0.19	0.06	-0.03	0.94
LAKE MICHIGAN						
Air Temperature	7.70	10.85	8.84	6.16	-1.14	0.85
Precipitation	0.24	0.12	0.24	0.12	-0.00	0.37
Runoff	0.20	0.09	0.18	0.06	0.01	0.72
Evaporation	0.17	0.14	0.18	0.08	-0.01	0.82
LAKE HURON						
Air Temperature	6.86	9.36	7.15	5.21	-0.29	0.88
Precipitation	0.26	0.10	0.26	0.11	-0.00	0.20
Runoff	0.25	0.16	0.24	0.12	0.01	0.67
Evaporation	0.20	0.14	0.22	0.05	-0.02	0.94
LAKE ST. CLAIR						
Air Temperature	10.39	9.68	11.11	5.84	-0.72	0.87
Precipitation	0.25	0.12	0.26	0.13	-0.01	0.32
Runoff	1.17	1.13	1.33	0.83	-0.16	0.72
Evaporation	0.26	0.22	0.34	0.09	-0.08	0.97
LAKE ERIE						
Air Temperature	9.81	9.29	10.66	5.50	-0.84	0.86
Precipitation	0.27	0.12	0.28	0.12	-0.01	0.14
Runoff	0.23	0.17	0.24	0.13	-0.01	0.69
Evaporation	0.29	0.20	0.28	0.05	0.01	0.96

*Units are feet over the lake for overlake precipitation, basin runoff, and lake evaporation; units are degrees Celsius for air temperature.

Table 5. One-Month Outlook Error Statistics for January 1984 - October 1986.

	Mean Actual*	Standard Deviation Actual*	Mean Model*	Root Mean Square Error*	Bias*	Corr. Coeff.
LAKE SUPERIOR						
Air Temperature	3.14	10.87	3.75	2.66	-0.62	0.97
Precipitation	0.24	0.09	0.24	0.09	-0.01	0.42
Runoff	0.19	0.08	0.20	0.05	-0.01	0.85
Evaporation	0.14	0.14	0.16	0.05	-0.02	0.95
LAKE MICHIGAN						
Air Temperature	8.38	9.83	8.45	2.10	-0.07	0.98
Precipitation	0.26	0.13	0.25	0.12	0.01	0.42
Runoff	0.22	0.09	0.20	0.07	0.02	0.70
Evaporation	0.15	0.13	0.16	0.07	-0.01	0.88
LAKE HURON						
Air Temperature	6.70	9.51	6.54	2.35	0.17	0.97
Precipitation	0.27	0.10	0.25	0.10	0.02	0.20
Runoff	0.27	0.13	0.24	0.08	0.03	0.84
Evaporation	0.17	0.13	0.19	0.04	-0.02	0.96
LAKE ST. CLAIR						
Air Temperature	10.54	9.90	10.21	2.07	0.33	0.98
Precipitation	0.26	0.13	0.25	0.14	0.01	0.15
Runoff	1.53	1.44	1.39	1.03	0.13	0.71
Evaporation	0.26	0.22	0.33	0.09	-0.07	0.98
LAKE ERIE						
Air Temperature	9.84	9.39	9.87	2.10	-0.02	0.97
Precipitation	0.28	0.12	0.27	0.13	0.01	0.08
Runoff	0.27	0.19	0.24	0.14	0.03	0.72
Evaporation	0.25	0.20	0.25	0.06	0.01	0.96

*Units are feet over the lake for overlake precipitation, basin runoff, and lake evaporation; units are degrees Celsius for air temperature.

Table 6. One-month Outlook Error Statistics for November 1986 - December 1988.

	Mean Actual*	Standard Deviation Actual*	Mean Model*	Root Mean Square Error*	Bias*	Corr. Coeff.
LAKE SUPERIOR						
Air Temperature	2.51	10.03	1.70	6.59	0.81	0.85
Precipitation	0.17	0.09	0.23	0.11	-0.06	0.42
Runoff	0.13	0.10	0.15	0.06	-0.02	0.79
Evaporation	0.16	0.13	0.21	0.08	-0.05	0.93
LAKE MICHIGAN						
Air Temperature	7.23	9.59	8.87	5.58	-1.64	0.85
Precipitation	0.19	0.12	0.20	0.12	-0.01	0.29
Runoff	0.16	0.05	0.16	0.04	0.00	0.73
Evaporation	0.14	0.13	0.18	0.11	-0.04	0.68
LAKE HURON						
Air Temperature	5.61	9.26	4.11	5.41	1.50	0.89
Precipitation	0.20	0.08	0.27	0.12	-0.06	0.20
Runoff	0.17	0.09	0.26	0.10	-0.09	0.90
Evaporation	0.20	0.14	0.23	0.06	-0.03	0.94
LAKE ST. CLAIR						
Air Temperature	8.71	9.40	8.91	5.54	-0.19	0.87
Precipitation	0.20	0.11	0.26	0.13	-0.06	0.47
Runoff	0.86	0.65	1.34	0.72	-0.48	0.86
Evaporation	0.23	0.23	0.31	0.10	-0.08	0.98
LAKE ERIE						
Air Temperature	8.32	9.37	8.80	5.39	-0.47	0.89
Precipitation	0.22	0.11	0.27	0.14	-0.05	0.02
Runoff	0.19	0.11	0.26	0.14	-0.07	0.56
Evaporation	0.25	0.20	0.24	0.04	0.01	0.98

*Units are feet over the lake for overlake precipitation, basin runoff, and lake evaporation; units are degrees Celsius for air temperature.

beyond one month. The exception is Lake Superior, which has consistent runoff forecast performance for all six forecast months. Runoff error statistics are high for Lake St. Clair because they are expressed as depths over the lake and that lake is quite small compared to its drainage area; runoff into Lake St. Clair is also the most variable. Runoff during the "wet" period is generally much higher than for the overall evaluation period. Except on Lake Superior, runoff is consistently underestimated during this period, by about 10% of the lakes' respective means. The "dry" period has much reduced runoff, with notably lower variability for Lakes Michigan and Huron. The runoff outlooks gave reduced runoff for Lakes Superior and Michigan, but not for the remaining lakes.

Lake evaporation is lowest on the upper, deep lakes and highest on the downstream, shallow lakes; it has the highest variability of the net basin supply components. Lake evaporation is a highly seasonal process, with almost all of a lake's annual evaporation occurring in a few fall and winter months, and virtually none occurring during the summer months. The strong seasonality of lake evaporation is also reflected in the high correlation between forecast and actual evaporation; the forecasts are doing a good job of capturing this seasonality for all evaluation periods, for all lakes. The exception is Lake Michigan, where air temperatures were significantly overestimated (bias = -1.14 and -1.64 degrees Celsius, respectively) during the overall and "dry" evaluation periods. During the "wet" period, lake evaporation was reduced on Lakes Superior and Michigan. The outlooks during this period also gave lower evaporation, but still overestimated it, except on Lake Erie. Forecasts are improved on Lake Michigan, where the temperature forecasts were much improved. During the "dry" period, lake evaporation was reduced for Lakes Michigan, St. Clair, and Erie. The outlooks reflected this for Lakes St. Clair and Erie, but not for Lake Michigan where the air temperature forecasts failed to reflect the cooler temperatures occurring during this period. Overall, evaporation forecasts appear best for Lake Erie, although performance for that lake deteriorates after the first month. On Lake Superior, the bias is much reduced after the first 3 months, suggesting biased NWS outlooks, biased selection of historic sequences, or biased estimation of lake heat storages used as initial conditions for subsequent modeling.

Probabilistic Outlooks

Unless it is perfect (and none are, as indicated by this analysis, Southam and Yee [1990], and Lee and Noorbakhsh [1990]), any deterministic net basin supply or lake level forecast inherently handicaps decision making. Whether considering one or several possible futures, final expression of a forecast as a "single best" time series simply can't convey all the information that is available to make a forecast. If only a single possible future is considered, the potential impacts of other, perhaps almost equally likely, futures are being ignored. If several possible futures are collapsed into a single time series, any expression of their diversity is lost.

Alternatively, probabilistic approaches enable expression of the potential diversity and inherent uncertainty of future conditions. Probabilistic outlooks may be generated by using multiple meteorologic sequences to produce multiple net basin supply forecasts, and then performing frequency analyses to define a probability distribution (Croley and Hartmann 1984). The NWS uses such an approach, known as Extended Streamflow Prediction (ESP) with their conceptual runoff models (Day 1985). However, that approach assumes that all the meteorologic sequences are equally likely to occur, and doesn't consider the limited ability of the NWS to forecast meteorology 1 to 3 months in advance. Suggested improvements to ESP include objectively assigning weights to historic sequences according to their similarity to meteorologic conditions of the current year (Day 1985); this represents an alternative meteorologic forecast not consistent with the NWS outlooks. We sought an approach that would explicitly consider the NWS weather forecast skill, yet also reflect the significant uncertainty of their outlooks and the recurring difficulty of finding few historic meteorologic sequences that closely match all categories of the NWS probability outlooks.

In selecting historic meteorology to use as forecast scenarios, we distinguish among three successively broader classes of sequences: those that are a "very good" match with the NWS outlook probabilities, those that are also a "fair to good" match, and then all historic sequences. Historic sequences within a given class are used with the Hydrologic Outlook Package to produce multiple net basin supply time series, and the extremes are plotted as in Figure 1.

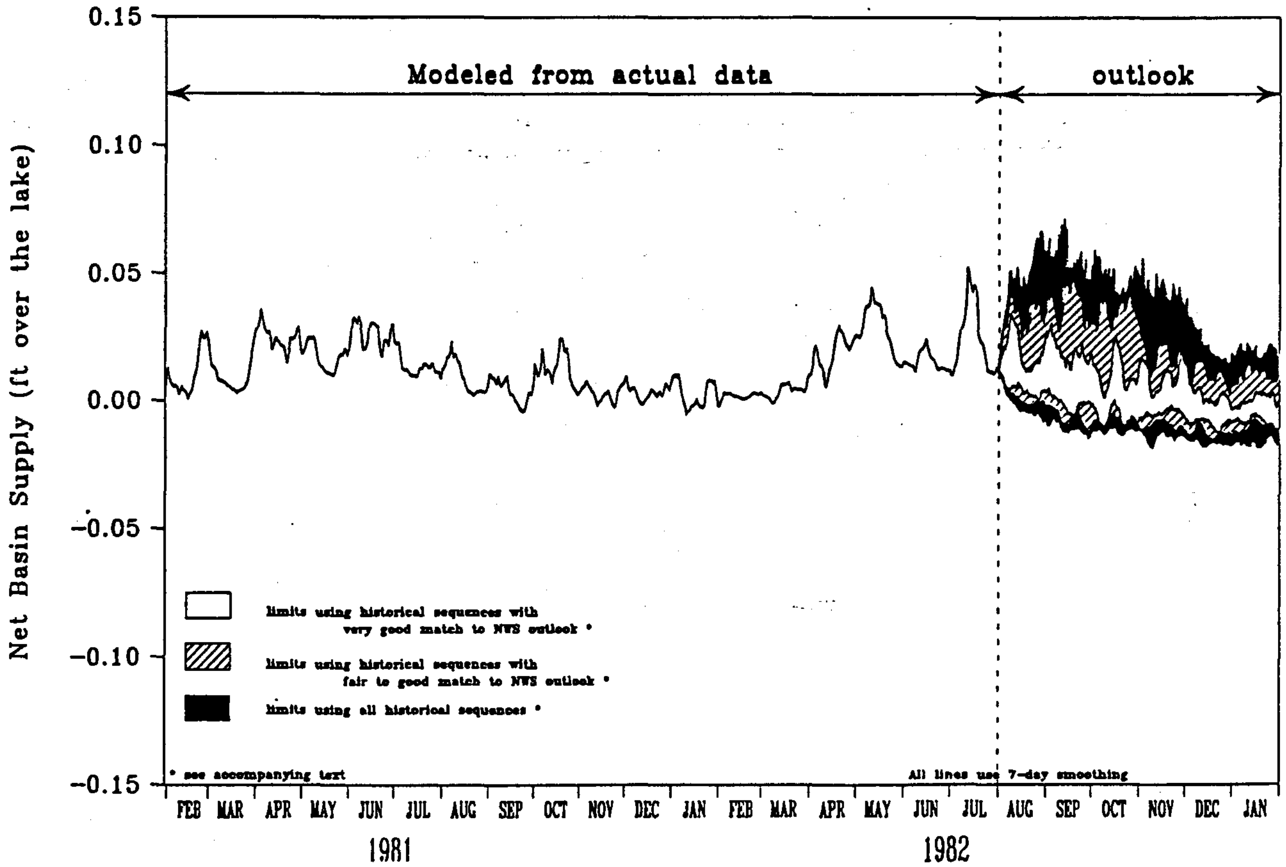

Figure 1. Example probabilistic outlook of Lake Superior net basin supplies.

The "very good" sequences match all categories of the NWS outlooks, within 3 percentage points. Typically, there are several historic sequences that fall into this class; they suggest the range of possible net basin supply conditions that decision makers should consider if they have high confidence in the NWS outlooks. However, there are cases where no historic sequence, or only one, matches the NWS outlooks so closely. In such cases, no limits would be shown for the "very good" class in the net basin supply outlook, making clear to users that there is greater uncertainty in potential net basin supplies over the forecast period because there is little or no historic precedent for the forecast meteorology. Selection of the additional "fair to good" sequences is more subjective than for the "very good" class. Sometimes several quite marginal matches are accepted, in the absence of any better alternatives. In such cases, sequences are selected to compensate for compromises in different categories. The broadest class reflects use of all historic meteorologic sequences. It is equivalent to the NWS ESP approach which, in effect, represents no confidence in the NWS outlooks; all historic sequences are considered equally likely to recur. Thus, the three envelopes of potential net basin supplies, as plotted in Figure 1, represent an incremental increase in the uncertainty about future meteorologic and hydrologic conditions.

The Hydrological Outlook Package is evaluated in this probabilistic application only for the overall evaluation period: August 1982 - December 1988. For each forecast month within the evaluation period, the maximum and minimum monthly net basin supplies and components, produced by the use of each of the three classes of forecast meteorology scenarios, are compared to what actually occurred. The frequency of actual conditions falling above or below the extremes given by the outlook package, expressed as non-exceedance probability estimates, is given in Table 7 for net basin supplies. These probabilities are estimates, based on past performance, that future forecast supplies will fall within the ranges predicted for each of the three forecast classes. For example, in Table 7, for Lake Michigan, for the range of forecast net basin supplies resulting from use of historic sequences that are "very good" matches with the NWS weather outlooks, we estimate an 80% probability that actual supplies will not exceed the maximum forecast net basin supply for this class, but also estimate a 13% probability that actual supplies will not exceed the minimum forecast supply for this class. Thus, we estimate a 67% probability that actual net basin supplies will fall within the range predicted by the "very good" class of forecasts, for the first month of the forecast period on Lake Michigan.

The sample size used to estimate the non-exceedance probabilities varies, and is given in Table 8 for the first month of the 6-month forecasts. Forecasting maximum and minimum net basin supply limits, as in Figure 1, requires a minimum of two forecast meteorologic scenarios selected from the historic record. Over the evaluation period, there were few historic sequences that provided a "very good" match to the NWS meteorologic outlooks, restricting the outlook package's ability to produce forecasts for this class. There were also some NWS outlooks that were so extreme that two historic sequences that matched even marginally could not be found, limiting the sample size for the "fair to good" class.

When historic sequences that are "very good" matches are available, the addition of "fair to good" matching sequences will produce net basin supply limits at least as broad as those resulting from use of "very good" sequences alone, since the forecast range for the "fair to good" class also includes "very good" sequences. However, when there are not enough "very good" matches to provide a maximum and minimum forecast range for that class, then consideration of only marginal matches can produce poorer forecasts of the possible ranges of supplies, since the NWS outlooks cannot be closely reflected by historic sequences. In such cases, the "very good" class would be absent in Figure 1 and decision makers may be advised to consider that even the broadest class (use of all historic sequences) doesn't reflect meteorologic conditions that the NWS expects to occur.

For forecasts where "very good" matches to the NWS meteorologic outlooks can be found in the historic record, the outlook package performs best for the first month on Lake Michigan, followed by Lakes Superior and St. Clair. The notable drop in performance for the second and third months, with gradual recovery in subsequent months, may suggest that the 3-month NWS outlooks for these lake basins are misdirecting historic sequence selection. For Lakes Huron and Erie, it may be that both the 1-month and 3-month NWS outlooks are misdirecting selection of historic sequences, since the probability estimates are worst for the "very good" class for the early months of the 6-month forecast period. For the lakes where the 1-month forecasts are best (Michigan, Superior, St. Clair), consideration of additional marginal sequences degrades forecast package performance, further suggesting that the NWS 1-month outlooks are good for these lakes and are thus guiding appropriate selection of historic sequences when there are good matches. In contrast, where the net basin supply outlooks are poor for the "very good" class (first through third month on Lakes Huron and Erie, and second and third months

Table 7. Net Basin Supply Forecast Non-exceedance Probability Estimate Based on Forecast Performance During August 1982 - December 1988.

Month	"Very Good" Matches Upper (%)	"Very Good" Matches Lower (%)	"Fair to Good" Matches Upper (%)	"Fair to Good" Matches Lower (%)	All Historic Sequences Upper (%)	All Historic Sequences Lower (%)
LAKE SUPERIOR						
1	69	8	69	20	94	3
2	33	8	57	11	91	5
3	75	0	67	11	91	5
4	67	33	67	15	92	5
5	75	25	68	15	92	5
6	83	50	65	13	93	6
LAKE MICHIGAN						
1	80	13	70	34	91	4
2	67	47	67	35	92	3
3	73	47	67	28	89	3
4	73	40	74	14	88	3
5	50	7	57	17	86	4
6	57	14	69	24	88	6
LAKE HURON						
1	56	28	71	24	92	5
2	75	38	64	21	91	5
3	63	21	70	22	91	4
4	75	42	71	26	91	4
5	71	46	68	35	92	4
6	71	33	72	22	92	4
LAKE ST. CLAIR						
1	84	26	78	30	96	3
2	78	56	82	37	95	3
3	67	28	74	28	96	1
4	78	33	73	27	96	1
5	67	44	62	20	96	1
6	78	39	61	29	96	1
LAKE ERIE						
1	63	48	63	39	97	1
2	63	41	64	32	99	1
3	70	26	67	18	97	3
4	70	26	67	22	99	3
5	70	26	65	20	99	3
6	78	22	74	25	99	3

Table 8. Number of Forecasts Used to Determine Non-exceedance Probability Estimates for the First Forecast Month.

	"Very Good" Matches	"Fair to Good" Matches	All Historic Sequences
Lake Superior	13	55	77
Lake Michigan	15	44	77
Lake Huron	25	68	77
Lake St. Clair	19	63	77
Lake Erie	27	56	77

on Lakes Superior, Michigan, and St. Clair), consideration of additional but marginal sequences improves forecast performance. This further supports the suggestion that the NWS outlooks are poor and misdirecting the selection of "very good" matching historic sequences.

For 33-39 years of historic record, simple ranking of historic conditions would produce non-exceedance probabilities of 3% and 97% for lower and upper net basin supply limits, respectively. Larger lower probabilities and smaller upper probabilities for the broadest class in Table 7 (use of all historic sequences) reflect effects of several factors: extreme conditions occurring during the evaluation period, use of a limited historic record for creating forecast meteorologic scenarios, modeling error, and error in estimation of actual conditions. On the other hand, smaller lower probabilities and larger upper probabilities reflect a combination of the lack of exceptional actual conditions and, for the early months of the forecast, additional information provided by the near real-time estimation of basin moisture and lake heat storage conditions, which subsequently influence hydrologic response to varied meteorologic conditions.

Probability estimates for net basin supply components (overlake precipitation, basin runoff, lake evaporation) are given in Table 9 for forecasts based on use of all historic meteorologic sequences. Differences from the 3% and 97% probabilities for precipitation directly reflect the extreme conditions experienced during the evaluation period, especially for the upper lakes. Actual precipitation was more extreme than reflected in the historic record since 1948, for fully 32% of the evaluation period for Lake Huron and 31% for Lake Superior. Lakes St. Clair and Erie had relatively few occurrences of precipitation more extreme than in the previous 33-39 years. The expanded range of probabilities for basin runoff, compared to overlake precipitation, reflects the effects of basin moisture storages which tend to dampen meteorologic variability. The probability ranges for lake evaporation are less broad than for runoff, except on Lake Huron, and may reflect extreme temperature conditions during the evaluation period. On Lake St. Clair, the minimum forecast evaporation exceeded actual evaporation for 65% of the forecasts for the first month, and for about 33% of the forecasts for the remaining months. The absence of similar conditions on Lake Erie suggests that extreme meteorologic conditions aren't involved, but that conceptual modeling errors may be large; the evaporation model was designed for large lakes with large heat storages, not for a small, shallow lake like Lake St. Clair.

Table 9. Overlake Precipitation, Basin Runoff, and Lake Evaporation Forecast Non-Exceedance Probability Estimates, Using All Historic Meteorologic Sequences, Based on Forecast Performance During August 1982 - December 1988.

Month	Overlake Precipitation Upper (%)	Overlake Precipitation Lower (%)	Basin Runoff Upper (%)	Basin Runoff Lower (%)	Lake Evaporation Upper (%)	Lake Evaporation Lower (%)
LAKE SUPERIOR						
1	88	19	95	5	100	14
2	88	17	95	5	99	14
3	87	13	95	7	99	15
4	85	14	95	7	99	11
5	86	14	95	7	99	8
6	89	15	94	8	99	10
LAKE MICHIGAN						
1	90	5	95	4	95	9
2	88	5	95	4	93	12
3	88	7	95	4	95	15
4	88	5	95	4	96	15
5	86	5	96	4	96	14
6	89	4	97	4	93	14
LAKE HURON						
1	86	18	96	6	99	5
2	88	11	96	6	99	1
3	88	11	96	7	99	1
4	88	11	96	7	100	1
5	88	12	96	7	100	1
6	92	13	96	7	99	1
LAKE ST. CLAIR						
1	96	14	95	3	100	65
2	95	7	95	3	100	34
3	95	8	95	3	100	32
4	95	5	95	4	100	32
5	95	5	96	4	99	33
6	95	4	96	4	96	33
LAKE ERIE						
1	96	6	92	3	94	3
2	97	4	92	3	87	4
3	97	3	92	3	87	3
4	97	3	92	4	84	3
5	97	3	93	4	84	4
6	99	3	93	4	85	3

Conclusions

Forecast errors fall into two broad categories: those associated with the NWS meteorologic probability forecasts and those associated with water supply estimation procedures. The latter includes errors associated with the subjective sampling of historic periods that "match" the NWS outlooks to some extent and with selecting from a limited sample (only 33-39 years are used). The latter also includes conceptual modeling errors for each component of net basin supplies (runoff, overlake precipitation, lake evaporation), and data errors associated with measurements (air temperatures, precipitation) and basic computations (e.g., overlake meteorology is estimated by overland meteorology, ignoring many lake effects). Additional analyses are underway to assess the error components associated with the NWS outlooks, use of a limited historic record, and the subjective sampling of the historic record to match the NWS outlooks.

As indicated by this paper, Southam and Yee (1990), and Lee and Noorbakhsh (1990), there is obviously much room for improvement in net basin supply forecasts. However, the Hydrologic Outlook Package does presently produce forecasts for some lakes, especially for the first month of the forecast period, that incorporate useful information provided by good extended weather outlooks. However, both deterministic and probabilistic net basin supply outlooks are hindered by notably poor NWS precipitation forecasts, which directly and adversely affect forecasting of basin runoff and overlake precipitation. Lake evaporation outlooks are sensitive to errors in air temperature forecasts. Use of a limited historic record particularly affected selection of historic meteorologic sequences during the "dry" evaluation period; no conditions since 1948 were of the same character as those forecast by the NWS during this period.

The deterministic outlooks are best on Lake Superior, where their performance is fairly consistent throughout the 6-month forecast period. Deterministic outlooks, however, have inherent limitations, since they provide only a single forecast time series. If only a single possible future is considered in making deterministic outlooks, the potential impacts of other, almost equally likely, futures are being ignored. If several possible futures are collapsed into a single time series, any expression of the diversity of potential future conditions is lost. Additionally, measures of performance of deterministic outlooks don't usefully express the confidence level to be accorded to future outlooks. Alternatively, probabilistic outlooks explicitly communicate the potential diversity and inherent uncertainty of future hydrometeorologic conditions. Our probabilistic net basin supply outlooks are most informative for 1-month forecasts for Lakes Michigan, Superior, and St. Clair, where NWS outlooks are good, enabling selection of appropriate historic meteorologic sequences.

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